

Gravitational-waves, ElectroMagnetic and dark-MAtter Physics Workshop

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Spectral Hardening of TeV y's in realistic extragalactic magnetic fields

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Anomalous transparency for Tev photons

- Universe should be opaque to ~TeV photons due to $\gamma^{VHE} \gamma^{bgk} \rightarrow e^+ e^-$ scattering
- However a high degree of transparency has been observed by H.E.S.S. and MAGIC collaborations



Possible explanations

 Conventional physics (secondary electromagnetic cascade generated from primary γ's and cosmic rays)

- W. Essey and A. Kusenko (2010)
- W. Essey, O.E. Kalashev, A. Kusenko and J.F. Beacom (2010)
- T.A. Dzhatdoev, E.V. Khalikov, A.P. Kircheva and A.A. Lyukshin (2016)
- Photon conversion into Axion-like particles in the magnetic field of the source and reconversion in Milky Way field
 - M. Simet, D. Hooper and P. D. Serpico (2008)
 - D. Horns, L. Maccione, M. Meyer, A. Mirizzi, D.M. and M. Roncadelli (2012)
- Photon to Axion-like oscillations in extragalactic magnetic field
 - A. De Angelis, O. Mansutti and M. Roncadelli (2008)
 - A. Mirizzi and D.M. (2009)
 - A. De Angelis, G. Galanti and M. Roncadelli (2011)

Axion-like particles

 Ultra light pseudo scalar Axion Like Particles (ALPs) with aγγ coupling are predicted in many extensions of the Standard Model (string theories, KK models, etc.)

$$\mathcal{L}_{a\gamma} = \frac{1}{2} \left(\partial^{\mu} a \; \partial_{\mu} a - m_a^2 a^2 \right) - \frac{1}{4} g_{a\gamma} F^{\mu\nu} \tilde{F}_{\mu\nu} a$$

 \Box Contrarily to QCD axions, ALPs mass and $a\gamma\gamma$ coupling are generally unrelated

Photons propagating in an external magnetic field can undergo γ -a oscillations



Photon-ALP oscillations

The evolution equation for the γ -a system relevant for this talk is

$$\begin{bmatrix} E - i \frac{\partial}{\partial x_3} + \begin{pmatrix} \Delta_{\rm pl} + \Delta_{\rm CMB} - \frac{i\Gamma_{\rm abs}}{2} & 0 & 0 \\ 0 & \Delta_{\rm pl} + \Delta_{\rm CMB} - i \frac{i\Gamma_{\rm abs}}{2} & \Delta_{a\gamma} \\ 0 & \Delta_{a\gamma} & \Delta_{a} \end{pmatrix} \end{bmatrix} \begin{pmatrix} A_{\perp} \\ A_{\parallel} \\ a \end{pmatrix} = 0$$

$$\Rightarrow \Delta_{a\gamma} \simeq 1.5 \times 10^{-2} \left(\frac{g_{a\gamma}}{10^{-11} \text{GeV}^{-1}} \right) \left(\frac{B_T}{10^{-9} \text{ G}} \right) \text{Mpc}^{-1}$$

$$\Rightarrow \Delta_{a} \simeq -3.2 \times 10^1 \left(\frac{m_a}{2 \times 10^{-8} \text{eV}} \right)^2 \left(\frac{E}{\text{TeV}} \right)^{-1} \text{Mpc}^{-1}$$

$$\Rightarrow \Delta_{\rm pl} \simeq -1.1 \times 10^{-7} \left(\frac{E}{\text{TeV}} \right)^{-1} \left(\frac{n_e}{10^{-3} \text{ cm}^{-3}} \right) \text{Mpc}^{-1}$$

$$\Rightarrow \Delta_{\rm CMB} \simeq 0.80 \times 10^{-1} \left(\frac{E}{\text{TeV}} \right) \text{Mpc}^{-1}$$

The last term accounts for the γ birefringence induced by the CMB photon background A. Dobrynina, A. Kartavtsev and G. Raffelt, Phys. Rev. **D** 91, 083003 (2015)

Limits on ALPs parameters



Conversion in Galaxy Clusters

- □ Galaxy clusters sometimes host Active Galactic Nuclei (AGNs) which are sources of very high energy (≿TeV) gamma rays
- The existence of turbulent magnetic fields with strength of the order of ~O(µG) in the intracluster medium (ICM) is well established through Faraday rotation measurements and nonthermal (synchrotron) emission at radio frequencies
- If some of photons are converted into ALPs in the ICM they can evade absorption. Further, ALPs can be reconverted into photons resulting in a cosmic "light shining through wall effect"
- The average (i.e., mediated on all possible magnetic field configuration) "photon intensity" can be written as

$$\begin{split} I_{\gamma}^{\mathrm{E}} &= P_{\gamma \to \gamma}^{\mathrm{MW}} I_{\gamma}^{\mathrm{MW}} + \left(1 - P_{\gamma \to \gamma}^{\mathrm{MW}}\right) I_{a}^{\mathrm{MW}} \\ &= \left[\exp\left(-\tau_{\gamma}\right) P_{\gamma \to \gamma}^{\mathrm{MW}} P_{\gamma \to \gamma}^{\mathrm{CL}} + \left(1 - P_{\gamma \to \gamma}^{\mathrm{MW}}\right) \left(1 - P_{\gamma \to \gamma}^{\mathrm{CL}}\right)\right] I_{\gamma}^{0}. \end{split}$$

where $P_{\gamma \to \gamma}^{MW}$ ($P_{\gamma \to \gamma}^{CL}$) are the galactic (cluster) photon "survival probability" and τ_{γ} is the optical depth for photon absorption

The effect can be observed as a spectrum harder than expected



D. Horns, L. Maccione, M. Meyer, A. Mirizzi, D. M. and M. Roncadelli, Phys. Rev. D86, 075024 (2012)



D. Horns, L. Maccione, M. Meyer, A. Mirizzi, D. M. and M. Roncadelli, Phys. Rev. D86, 075024 (2012)

Conversion in MilkyWay magnetic field



Extragalactic Magnetic Field (EFM)

- Extragalactic magnetic fields are believed to pervade the universe
- They can be generated by primordial primordial fields and amplified in extragalactic medium
- They are compatible with an average field strength of B≲O(1 nG) with a coherence length I_c≲O(1 Mpc)
 M.S. Pshirkov, P.G. Tinyakov and F.R. Urban (2106)
- □ Also lower limit apply B≥O(10⁻¹⁶ G) from non observation of secondary photons from TeV source

A.N. Neronov and I. Vovk (2010)

The Magnetized Cosmic Web

 IGM is usually modeled as a network of "cells" with almost constant magnetic field B~O(nG) and coherence length I_c~O(1Mpc) with uncorrelated random directions



"Realistic" IGM Fields

- Full MagnetoHydroDynamical simulations produced using the cosmological code *Enzo* (F. Vazza, M. Brüggen, C. Gheller and P. Wang, 2014)
- Uniform primordial seed field of B₀=1 nG (comoving) for each component, starting from z=38 and for a comoving volume of 200³ Mpc³, sampled using a fixed grid of 2400³ cells and 2400³ dark matter particles
- The model incorporates the dynamical interplay between structure formation (e.g. gas compression onto filaments, galaxy groups and clusters), rarefactions (onto voids) and further dynamo amplification where turbulence is well resolved

Files available at site

http://cosmosimfrazza.myfreesites.net/the magnetic cosmic web

Realistic IGM Fields



Projected magnetic field intensity for 2400^3 simulation of a $(50 \text{ Mpc})^3$ volume at z = 0

🖵 Vazza et al. 2014



Realistic IGM Fields



D.M., F. Vazza, A. Mirizzi, M. Viel PRL 119 (2017) 101101

Propagation

When peaks are encountered a massive regeneration takes place



Transfer function vs energy



PDF of transfer function



Transfer function for cells...



...and for realistic B field



Allowed zone



Conclusions

- Anomalous transparency can be an hint for photon-ALP conversions in astrophysical magnetic fields,
- One possibility is conversion in Cluster field and reconversion in Milky way field
- Realistic simulations of IGM field are now available
- Enhancement of the transfer function respect to those calculated by the simplified cell model
- Larger area of parameters can be probed
- Next step: include source and galactic magnetic field